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EFFECTS OF AREA-OF-INTEREST DISPLAY CHARACTERISTICS ON VISUAL SEARCH PERFORMANCE AND HEAD MOVEMENTS IN SIMULATED LOW-LEVEL FLIGHT

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An investigation was conducted to evaluate the influence of area-of-interest (AOI) display characteristics on target detection performance and head movements. Two AOI display conditions were compared: a small (26.44 by 21.51 deg horizontal and vertical), higher resolution AOI and a large (40.00 by 30.00 deg horizontal and vertical), lower resolution AOI. The observers viewed a computer-generated visual scene consisting of three-dimensional cylinder-shaped objects placed upright on a desert-like terrain surface. Black bands were modeled on some of the cylinders, and the bands constituted the targets. Cylinder height and diameter were varied along with the position of the banded cylinders relative to the flight path of the simulated aircraft. Both pilots and nonpilots were used as observers. Results indicate that target detection distance varied as a function of AOI condition and the height and diameter of the cylinders on which the bands were placed, but not type of observer. Both horizontal and vertical head movements were sensitive to the differences between the AOI conditions, and the vertical movements were also influenced by type of observer. We recommend that the small, higher resolution AOI be used in situations where greater target detection distance and higher image detail are required.

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PREFACE

The present investigation was conducted at the Aircrew Training Research Division of the Armstrong Laboratory to compare the effects of area-of-interest (AOI) display conditions on target detection performance and head movement characteristics. This research effort was supported by the University of Dayton Research Institute, Contract No. F33615-90-C-0005, in conjunction with Work Unit Nos. 1123-03-85, Flying Training Research Support, and 1123-32-01, Visual Display System Functional Requirements. The contract monitor was Ms. Patricia A. Spears. The work unit monitor was Dr. Byron J. Pierce.

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EFFECTS OF AREA-OF-INTEREST DISPLAY CHARACTERISTICS ON VISUAL SEARCH PERFORMANCE AND HEAD MOVEMENTS IN SIMULATED LOW-LEVEL FLIGHT

INTRODUCTION

Visual systems employing area-of-interest (AOI) displays have been developed for flight simulator applications in response to the training demands for greater display resolution and total field-of-view (FOV) size (e.g., Barber, 1986; Browder & Chambers, 1988; Chambers, 1982; Neves, 1984; Spooner, 1982; Tong, 1990). An AOI display consists of a high-resolution inset that is surrounded by a much larger background display with lower resolution. The AOI may be moved within the visual field wherever the high resolution imagery is required by the user. Movement of the AOI may be controlled in various ways. The AOI may be target-tracked, eye-tracked, head-tracked, or simultaneously eye- and head-tracked.

Two of the most important design decisions associated with the development of visual systems equipped with AOI displays concern the size and level of resolution of the AOI to use. The dimensions of the AOI that are employed dictate the area of the visual scene that is encompassed within the high-resolution inset at any given moment, and the resolution of the AOI determines the simulated distances at which objects can be detected as well as the level of image detail that is visible at a particular distance. Due to the tradeoff between AOI FOV and resolution, increasing AOI size will result in a concomitant reduction in AOI resolution and vice versa. Thus, if AOI size is increased so that a larger area of the visual scene is within the AOI, AOI resolution will be reduced and visual detection distances and image detail will be degraded. Conversely, if the size of the AOI is reduced to enhance detection distances and image detail, a smaller area of the visual scene will be presented in the AOI.

Research has shown that user performance can be adversely affected if the AOI is too small or if the level of resolution is insufficient for the task. Turner (1984) investigated the effects of three different eye-tracked AOI FOV sizes (i.e., 12, 18, and 28 deg in diameter with resolution levels of 2.0, 3.0, and 4.75 arc min per line pair, respectively) along with various other display conditions on flight path deviation and target detection performance. It was observed that the average of the mean deviations from the path and the number of missed targets was greater for the smallest (higher resolution) and largest (lower resolution) AOI sizes when compared with the nominal, 18-deg AOI. These findings suggest that the FOV size associated with the 12-deg AOI was too small and that the lower resolution corresponding to the largest AOI size was not sufficient for the tasks.

In addition to having an adverse effect on user performance, research has demonstrated that reducing the FOV size of the high-resolution inset can influence head movement characteristics when searching for targets (Venturino & Wells, 1990; Wells & Venturino, 1990; Wells, Venturino, & Osgood, 1988). In this research, a helmet-mounted display (HMD) was used and the visual imagery was head tracked. The HMD provided a high-resolution inset superimposed within a background visual field that was 120 deg horizontal by 60 deg vertical. Five superimposed inset sizes were compared that ranged from 20 deg by 20 deg to 120 deg by 60 deg horizontally and vertically. Visual stimuli representing targets and threats were presented, and the stimuli were visible only in the high-resolution inset. The investigators reported that the smaller inset sizes had a disruptive effect on task performance. In addition, head displacement was greater and head velocity was slower with the smaller inset sizes.

Because both AOI display resolution and FOV size can affect user performance, the particular AOI resolution/FOV combination that is implemented could impact the training effectiveness of a flight simulator that employs AOI display technology. Use of a higher resolution AOI would facilitate user performance in tasks that involve visual detection over long distances and tasks that require high detail, but might impair performance in tasks that are FOV sensitive. Alternatively, a large AOI FOV could facilitate performance in FOV-dependent tasks, but would decrease detection distances and image detail. To minimize the adverse effects associated with an AOI FOV that is too small or AOI resolution that is not adequate, the most efficient approach would be to employ an AOI that provides the best resolution and FOV size combination across the range of tasks that would be trained in the simulator.

Recently, a multiphase flight simulator research program was initiated at the Aircrew Training Research Division of the Armstrong Laboratory (AL/HRA) to evaluate the effects of different AOI conditions on user performance and head movements in a variety of visually related flight tasks, such as low-altitude tactical navigation, low-altitude tactical formation flight, and conventional and tactical weapon deliveries. The goal of this research program is to determine which of the AOI conditions evaluated is best for the various tasks. Two investigations in the AOI research program have now been conducted. The visual simulation system used in these investigations was the Limited Field-of-View Dome (LFOVD), which provides a head-tracked AOI display. The initial investigation in the research program has been documented elsewhere (Warner, Hubbard, & Serfoss, 1992) and is summarized below following the description of the LFOVD; the second investigation is the subject of this report.

LFOVD Visual Simulation System

The LFOVD employs a 24-ft-diameter dome, and a fully operational F-16A simulator cockpit is enclosed within the dome. The viewing distance from the eyepoint in the cockpit to the interior surface of the dome is 12 ft. An AOI display is projected onto the dome surface, and two different AOI display configurations are available. The vertical and horizontal FOV dimensions, resolution, and addressability of the two AOI displays are specified in Table 1. A blend region is included between the AOI and the surrounding display to avoid a sharp edge between the high-resolution inset and lower resolution surround. The blend regions of the small and large AOI sizes are 2.5 and 5.0 deg, respectively. The instantaneous FOV, which is defined by the maximum dimensions of the surrounding visual field, is 60 deg vertical by 140 deg horizontal. The AOI is head-tracked and can be rotated up to 90 deg left and right, 40 deg upward, and 22 deg downward from a point directly in front of the cockpit at eye level. The AOI is centered in the background display, and the background moves in concert with the AOI. A Polhemus head-tracker is used to measure head position.

Table 1. LFOVD AOI Display Characteristics

	FOV size (deg)		Resolution (deg)		Addressability (arc min per pixel)	
AOI Size	vert	horiz	vert	horiz	vert	horiz
Small	21.51	26.44	0.077	0.081	1.41	1.55
Large	30.00	40.00	0.121	0.132	2.31	2.55

Note. Resolution is defined as the width of the line spread function at 50% of the line's maximum luminance, which is a standard measure of resolution (Murch & Virgin, 1985).

Computer-generated color imagery is presented in the AOI and surrounding displays. A General Electric Advanced Visual Technology System (AVTS) computer-image generator provides the imagery, and two General Electric light-valve projectors are used to display the imagery, one for the AOI and one for the surrounding visual field. The output characteristics of the light-valve projectors are described by Howard (1989). Optical lenses and filters are used to shape the AOI and surrounding field and to position the blend region between the AOI and background displays. The light-valve projectors are located in the dome above the simulator cockpit, along with the servosystem hardware that positions the AOI in the direction the user's head is aimed.

Initial AOI Investigation

The initial investigation in the AOI research series (Warner et al., 1992) was conducted to determine the effects of the LFOVD AOI display conditions and various stimulus characteristics on visual detection thresholds. The stimuli were banded and plain (nonbanded) three-dimensional cylinder-shaped objects that were placed upright on a flat, desert-type terrain surface. Two band sizes were investigated, a 4-ft- and an 8-ft-high band, which encircled the cylinders midway between the top and bottom. The heights and diameters of both the banded and plain cylinders were also varied. The heights of the cylinders were 50, 75, and 100 ft; the cylinder diameters used were 25, 50 and 75 ft. These dimensions were crossed to provide nine different cylinder sizes. The stimuli were presented in both the small and large AOI displays, and approaching and receding detection thresholds were obtained for both the cylinder bands and the plain cylinders.

The analysis of the detection thresholds associated with the cylinder bands indicated that: (a) the detection distances were about 50% greater on the average with the small (higher resolution) AOI size, (b) the distances were about 2,000 ft greater for the larger (8-ft-high) cylinder band, and (c) the band detection distances increased as both the heights and diameters of the banded cylinders increased. The detection distances for the plain cylinders were mainly governed by the image generator load management parameters, which prevent visual system overload from the presence of an overabundance of objects in the visual scene.

Objectives and Scope of the Present Investigation

Two of the most common pilot activities in flight training are visual search and detection, which are encompassed in air-to-air combat within visual range, air-to-ground weapon deliveries, and low-altitude navigation. In air-to-air combat training, the pilot must search for and locate the adversary aircraft in the environment. When ingressing the target area during an air-to-ground attack, the pilot must find the designated target and then visually track the target until the weapons are released. In low-altitude navigation, the pilot is required to scan the environment to locate visual cues that enable him to maintain the proper course.

Due to the importance of visual search and detection in flight training, the AOI requirements for these activities were addressed in the second AL/HRA AOI investigation, which is presented herein. The specific objectives of this investigation were to: (1) compare the effects of the LFOVD AOI display conditions on detection distances in a visual scanning task and (2) evaluate the influence of the AOI displays on head movements during visual scanning.

Computer-generated imagery was presented that portrayed three-dimensional cylinder-shaped objects on a flat, desert terrain. The cylinders were located in cylinder "corridors" that were 250,000-ft long, and one cylinder appeared every 2,000 ft along the corridors. The heights and diameters of the cylinders were varied, and the cylinders were placed up to 1 mi on either side of the flight path of the simulated aircraft, which was on the centerline of the corridors. A 4-ft-high band encircled some of the cylinders, which constituted the target stimuli. There were 4 banded and 122 nonbanded cylinders in a corridor. The subjects' task was to scan the visual scene and signal the presence of the targets as soon as they were detected. The subjects served as observers only; they had no control of the aircraft. The aircraft was flown in a straight path, at an altitude of 150 ft above ground level (AGL) and at an airspeed of 500 kt. Each subject performed the task four times, twice with the small (higher resolution) AOI size and twice with the large (lower resolution) AOI. The independent variables were: AOI condition, banded cylinder height, banded cylinder diameter, target location, and type of observer. Target detection distances and a variety of head movement data were collected during the trials. Two groups of observers were compared, pilots and nonpilots.

METHODS

Observers

A total of 12 male observers participated, 6 pilots and 6 nonpilots with normal or corrected visual acuity. The mean, minimum, and maximum flight hours of the pilots were 2,134, 298, and 3,660, respectively. Contrast sensitivity was measured for each observer using the Vistech Consultants, Inc., Vision Contrast Test System (VCTS), Model 6500. Test stimuli were monochromatic sinusoidal gratings that varied in contrast. The spatial frequencies of the gratings were 1.5, 3, 6, 12, and 18 cycles per deg. Test results indicated that the observers had normal contrast sensitivity functions.

Flight Simulator

The LFOVD visual simulation system was employed in the investigation. The cockpit instrument lights, cockpit head-up display (HUD), and lights in the dome were extinguished during testing to provide a dark ambient environment. The only light was from the display imagery. Both the small and large AOI sizes were evaluated, and the AOI displays were head tracked. Head movement data, which consisted of the azimuth and elevation angular rotations of the observer's head, were recorded during the simulation at a rate of 60 samples per second.

The gun trigger switch on the side-arm control stick of the F-16A simulator cockpit was operational, which the observer pressed when a target was detected. A pulsating gun sound was emitted when the trigger was pressed. None of the other cockpit controls were operational. Simulated aircraft engine noise was produced in the simulator during the trials. Headsets were provided to permit communication between the observers and the investigators.

During testing, the investigators were located at the experimenter/operator control console in a room adjacent to the simulator. The console contained several display monitors and touch-sensitive displays for monitoring the observers' simulated flights and controlling the flight conditions. Observer response data were presented on one of the monitors after each trigger press.

Visual Database

A visual database was modeled consisting of three-dimensional cylinder-shaped objects on a flat desert terrain. The cylinders were placed upright on the terrain surface and were closed at the top, resembling petroleum storage tanks in an oil field. There were no other structures or natural objects, such as trees and bushes, in the visual environment. The cylinders were a light green, the sky was blue, and the ground was dark tan and mottled with irregular black shapes to simulate desert terrain.

Three cylinder corridors were produced, and each corridor was 250,000 ft long. There were 126 cylinders in each corridor, one at the starting ends and then one every 2,000 ft. The cylinders were placed 1,056 ft, 3,168 ft, and 5,280 ft (one mi) on either side of the centerline of each corridor. The corridors ran parallel to one another and were spaced far enough apart so that only the cylinders in the corridor the observer was positioned would be visible. Also, the desert texture pattern extended well beyond the sides and ends of the corridors.

Six cylinder sizes were used in the corridors and the locations of the various sizes were randomly assigned. The six sizes were formed through the combination of three cylinder heights (50, 75, and 100 ft) and two cylinder diameters (25 and 75 ft). The six cylinder sizes are specified in Table 2. Each cylinder size was modeled with a 4-ft-high black band that could be turned on and off by the image generator.

Table 2. Cylinder Sizes

Cylinder size	Cylinder height (ft)	Cylinder diameter (ft)
1	50	25
2	50	75
3	75	25
4	75	75
5	100	25
6	100	75

When the cylinder band was turned on, the band was generated on the cylinder, and when the band was turned off, it was not generated. The cylinder bands served as the target stimuli in the present investigation.

The bands were placed midway between the top and bottom of the cylinders, and they completely encircled the cylinders. Because the bands wrapped around the cylinders, the width of the bands varied as a function of the diameter of the cylinders. As a result, the sizes of both the bands and the cylinders were greater with the larger of the two cylinder diameters. For the 25-ft-diameter cylinders, the area of the bands was 100 sq. ft (4 ft x 25 ft) while the area of the bands was 300 sq. ft (4 ft x 75 ft) for the 75-ft-diameter cylinders. The sizes of the bands were not influenced by the variations in cylinder height; only the total area of the cylinders differed.

Two separate target sets were produced, and there were 36 targets to a set. In each target set, the three corridors were each presented three times for a total of nine corridor presentations. Four targets were presented in each of the nine corridors to provide the 36 targets. The cylinder bands were selectively turned on and off in each corridor presentation so that each of the six banded cylinder sizes would appear once at each of the six lateral (left and right) distances from the corridor centerline across the nine corridor presentations. The banded cylinder sizes and locations used in each corridor presentation were randomized, and two different random target assignments were used in the two target sets. The simulated distance from the first cylinder in a corridor to the first target and the distance between targets was randomly varied between 40,000 and 50,000 ft in 2,000-ft increments, and each separation was used an equal number of times in both target sets.

One of the corridors was used for observer practice in which all six of the banded cylinder sizes were presented, one at each of the six lateral target locations. The corridor was started from the opposite end in the practice trial so that the subjects did not view one cylinder sequence more often than the others. The targets were spaced closer together longitudinally in the practice corridor presentation than when the four targets were presented in the test trials, but not sufficiently close that two targets were simultaneously in view.

The luminance levels were matched across the small AOI, large AOI, and background displays and are provided in Table 3. A Pritchard Spectra Photometer, Model 1980A, was used to obtain the luminance measurements, and the photometer was located at the observer eyepoint. The respective height and diameter of the banded cylinder used for these measurements were 100 ft by 25 ft. The cylinder luminance was measured halfway between the band and the bottom of the cylinder and midway between the left and right sides of the cylinder. The band luminance was measured midway between the top and bottom and the left and right ends of the band. The cylinder was positioned at a simulated distance of 500 ft for the measurements, and the aircraft was 70 ft above the ground. The sky luminance was measured about five deg above the horizon, and a solid tan area in the ground texture was used for the ground luminance measurement. The luminance levels were calibrated each day of testing to ensure that they were the same for each observer in each session.

The luminance contrast between the cylinder and band was 92.91%, 92.3% between the cylinder and the ground, and 0.1% between the cylinder band and the ground. Contrast was determined using the equation:

$$\text{Contrast (\%)} = \frac{\text{Lmax} - \text{Lmin}}{\text{Lmax}} \times 100$$

where Lmax is the luminance of the brighter area and Lmin is the luminance of the darker area.

Table 3. Luminance Levels within the Small AOI, Large AOI, and Background Displays

	Luminance (fL)
Cylinder	1.27
Band	0.09
Ground	0.10
Sky	0.06

As the simulated aircraft traversed the corridors, the cylinders transitioned into the visual scene at a distance of 50,000 ft. The distance could not be increased because the additional cylinders beyond this distance resulted in an overload of the image generator. To prevent the cylinders from abruptly "popping" into the scene at 50,000 ft, a very light simulated haze was used which thickened at the horizon. The cylinders appeared to transition out of the haze and realistically increase in clarity and brightness.

Procedure

Each observer participated in four separate test sessions. The two LFOVD AOI display sizes were factorially crossed with the two target sets to provide four experimental conditions, and each observer was subjected to each of the conditions, one in each session. The order in which the four experimental conditions was presented to each participant was randomized, and at least a day elapsed between sessions. In each session, the observer was presented the practice cylinder corridor and then the nine corridors in the target set, and the order in which the nine corridors were presented was randomized. Each corridor presentation constituted a separate test trial, and the duration of each trial was 3 min and 25 s. Between trials, a computer-generated cloud-like mask was presented in the AOI and background displays, and the simulator was frozen. When the observers were ready to start a trial, they verbally signaled the experimenter. The simulator was then unfrozen and the mask was removed to reveal the simulated visual scene. The simulator was initialized 20,000 ft in front of the first cylinder in the corridor for each trial, and the trial was terminated 50,000 ft before the end of the corridor, after the observers had passed the four targets. The distance between the start point and the first target and the distance between the last target and termination point varied as a function of the randomized target separations that were used.

The speed and flight path of the simulated aircraft were computer controlled. The aircraft traversed the centerline of cylinder corridors at a speed of 500 kt and at an altitude of 150 ft AGL.

The observers' task was to scan the visual scene for the targets and to press the trigger switch on the side-arm controller in the cockpit when they detected a target. Response feedback was verbally provided by the experimenters after each trigger press. A response was considered correct if the target was in the AOI inset and if the target was within visual range. The corresponding target detection threshold distances established in the initial AOI investigation (Warner et al., 1992) were used to determine when the targets were within visual range in the present investigation. A display message indicating whether the observer's response was correct or incorrect was provided at the simulator experimenter/operator control console for use as the response feedback. A message was also displayed at the console if the observer missed a target; missed-target feedback was also provided.

Standardized instructions were provided prior to the start of the first session and the task requirements were reviewed preceding each of the following three sessions for each observer. The instructions described the purpose of the investigation, the visual simulation system, visual scene, practice and test trials, task requirements, and head tracker. The observers were instructed to place the AOI over the target when they pressed the trigger to indicate they detected the target. The subjects were advised that there were six targets in the practice trial and four in each of the nine experimental trials. The head tracker was activated after the instructions were given, and the observers were asked to look around to become accustomed to the movement of the AOI.

The practice trial was presented in each of the observer's four test sessions. The practice trial was repeated if necessary until the observers correctly located each of the six targets in the corridor. The test trials were started as soon as the observers were ready after the practice trial. The time between trials was paced by the observer, and usually only a few seconds elapsed before the observer signaled to continue. The observers were not permitted to leave the simulation between trials. Due to the length of the instructions, the observers were dark adapted by the time the practice trials were initiated. Each of the sessions lasted from 45 to 60 min.

Performance Measures

The following target detection and head movement measures were employed in the present investigation:

A. Target detection measures
   1. Target detection distance
   2. Response errors
   3. Missed targets

B. Head movement measures
   1. Horizontal head reversal frequency
   2. Mean horizontal head excursion duration
   3. Standard deviation horizontal head excursion duration
   4. Mean horizontal head excursion amplitude
   5. Standard deviation horizontal head excursion amplitude
   6. Vertical head reversal frequency
   7. Mean vertical head excursion duration
   8. Standard deviation vertical head excursion duration

9. Mean vertical head excursion amplitude
10. Standard deviation vertical head excursion amplitude

The target detection measures are defined as follows:

Target detection distance. The slant range distance in feet from the observer to the target when the trigger was pressed.

Response errors. The frequency that the trigger was pressed when there was no target in the AOI or the target was beyond visual range.

Missed targets. The frequency that targets passed abeam the aircraft and were not detected by the observer.

The operational definitions of the head movement measurements are as follows:

Horizontal head reversal frequency. The frequency that the direction of rotation of the observer's head reversed from right to left and left to right from any position in space.

Horizontal head excursion duration. The elapsed time of the head excursion between one reversal point and the next in the horizontal direction.

Horizontal head excursion amplitude. The angular extent of the head excursion between one reversal point and the next in the horizontal direction.

Vertical head reversal frequency. The frequency that the rotation of the observer's head reversed direction from upward to downward and downward to upward.

Vertical head excursion duration. The elapsed time of the head excursion between one reversal point and the next in the vertical direction.

Vertical head excursion amplitude. The angular extent of the head excursion between one reversal point and the next in the vertical direction.

Once the participants had detected a target and pressed the trigger, they typically ceased to actively scan the visual scene until the target had passed because they had been informed that only one target would be in view at a time. It was considered prudent to ignore the head movement data in this time interval and use just the data for the period between the point when a target passed abeam and when the next trigger press occurred. This approach would have produced variable scanning periods, however, because the point at which the trigger was pressed after the previous target passed varied between participants and as a function of AOI size. To circumvent this problem, a constant time interval immediately preceding the trigger press was used. The duration of the interval was 13.67 s, which represented the shortest time period (longest detection distance) in the investigation between the point when a target passed and when the trigger was pressed for the next target. The first correct trigger press to a target defined the end point of each scanning interval. Since there were four targets in a corridor presentation, there was a maximum of four scanning intervals for each corridor. To avoid the inclusion of micro reversals such as twitches in the head movement data, only head excursions that were at least 1 deg in magnitude were recorded.

Because the noise characteristics of the head-tracking system were unknown, a comprehensive noise analysis was performed. For this analysis, the component of the head tracker that is normally attached to the observer's headset was statically positioned in the simulator cockpit. Raw horizontal and vertical head data were then collected for three different simulated head positions: (a) approximately 0 deg vertical and horizontal, (b) approximately 0 deg vertical and 60 deg horizontal, and (c) approximately 20 deg vertical and 0 deg horizontal. The horizontal and vertical data samples for each position were subjected to a fast Fourier transform (FFT) analysis encompassing the frequency range from DC to 15 Hz. The analysis indicated that at each of the positions measured, the noise was random and there were no appreciable peaks. The peaks were less than 0.0085 deg at each frequency with two exceptions. In the 0 deg vertical and horizontal position, there was a peak of 0.0116 deg at 6.161 Hz associated with the vertical data, and there was a peak of 0.0153 deg associated with the horizontal data at 4.747 Hz. In view of the extremely small amplitude of the noise, the noise was not removed from the head movement data.

RESULTS

Target Detection Measures

The target detection distance data were subjected to a five-factor analysis of variance (ANOVA) with repeated measures. The within-subjects factors were: AOI size, target position from centerline, banded cylinder height, and banded cylinder diameter. The between-subjects factor was type of observer. The levels of the five factors were as follows:

1. AOI size: small and large
2. Target position: 1,056 ft, 3,168 ft, and 5,280 ft
3. Banded cylinder height: 50 ft, 75 ft, and 100 ft
4. Banded cylinder diameter: 25 ft and 75 ft
5. Type of observer: pilots and nonpilots

For the target position factor, the target detection distances associated with the target positions on the corresponding left and right sides of the corridors were pooled. For example, the detection distances for the targets at 1,056 ft on the right side of the corridors were combined with the detection distances for the targets at 1,056 ft on the left side. The target detection distances obtained in the two target sets were also pooled in the data analysis.

Statistically significant main effects were obtained in the analysis for: (a) AOI size, $F(1,385) = 1583.83$, $p < 0.01$; (b) target position, $F(2,385) = 12.52$, $p < 0.01$; (c) banded cylinder height, $F(2,385) = 475.56$, $p < 0.01$; and (d) banded cylinder diameter, $F(1,385) = 1277.48$, $p < 0.01$. The main effect of the type of observer was not significant, indicating that the target detection distances did not differ between the pilots and nonpilots.

In addition, three two-way interactions and one three-way interaction were statistically significant. The significant two-way interactions were: (a) target position by banded cylinder diameter, $F(2,385) = 10.58$, $p < 0.01$; (b) AOI size by banded cylinder diameter, $F(1,385) = 17.75$, $p < 0.01$; and (c) banded cylinder height by banded cylinder diameter, $F(2,385) = 129.72$, $p < 0.01$. The significant three-way interaction was: AOI size by banded cylinder height by banded cylinder diameter, $F(2,385) = 9.41$, $p < 0.01$.

The mean target detection distances associated with the two-way target position by banded cylinder diameter interaction are presented in Figure 1. Pair-wise comparisons of the means using the least-significant difference (LSD) procedure indicated that difference in detection distance between the 1,056-ft and 3,168-ft target positions, the 1,056-ft and 5,280-ft positions, and the 3,168-ft and 5,280-ft positions for the 25-ft-diameter cylinders were statistically significant ($p < 0.05$). The differences between the 25-ft- and 75-ft-diameter cylinders were also significant at each of the three target positions. Inspection of the means in Figure 1 shows that the detection distances were greater for the bands on the 75-ft-diameter cylinders than on the 25-ft-diameter cylinders and that the detection distance of the bands on the 25-ft-diameter cylinders increased as the distance of the target position from the centerline increased.

The three-way interaction is depicted in Figure 2. LSD tests indicated that all of the pair-wise mean comparisons were statistically significant ($p < 0.05$). Several relationships are evident in Figure 2. First, the detection distances were greater with the smaller (higher resolution) AOI than the larger (lower resolution) AOI, except that the visibility of the bands on the 100-ft-high by 75-ft-diameter cylinders in the large AOI was

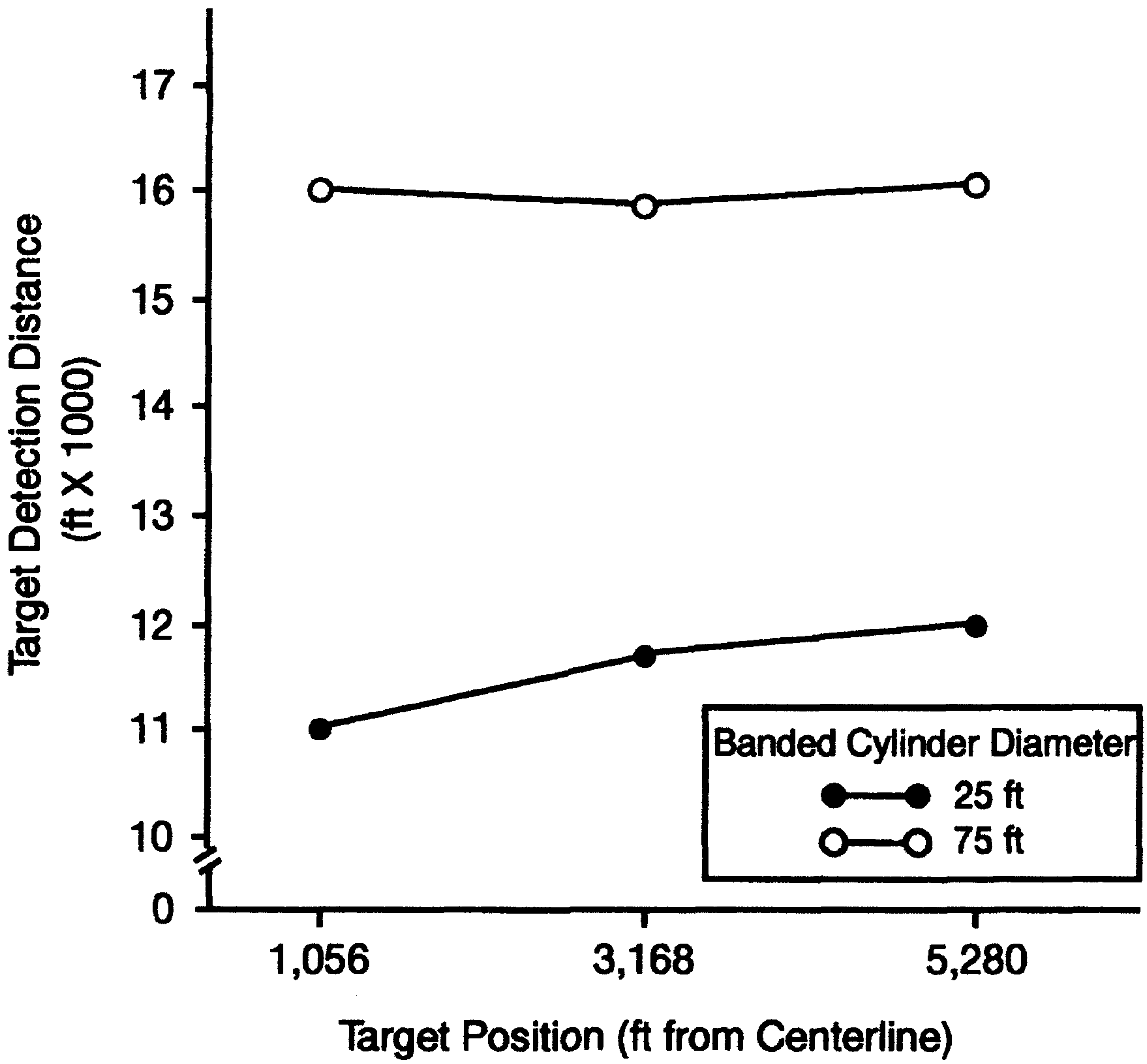

Figure 1
Mean Target Detection Distance as a Function of Target Position and Banded Cylinder Diameter

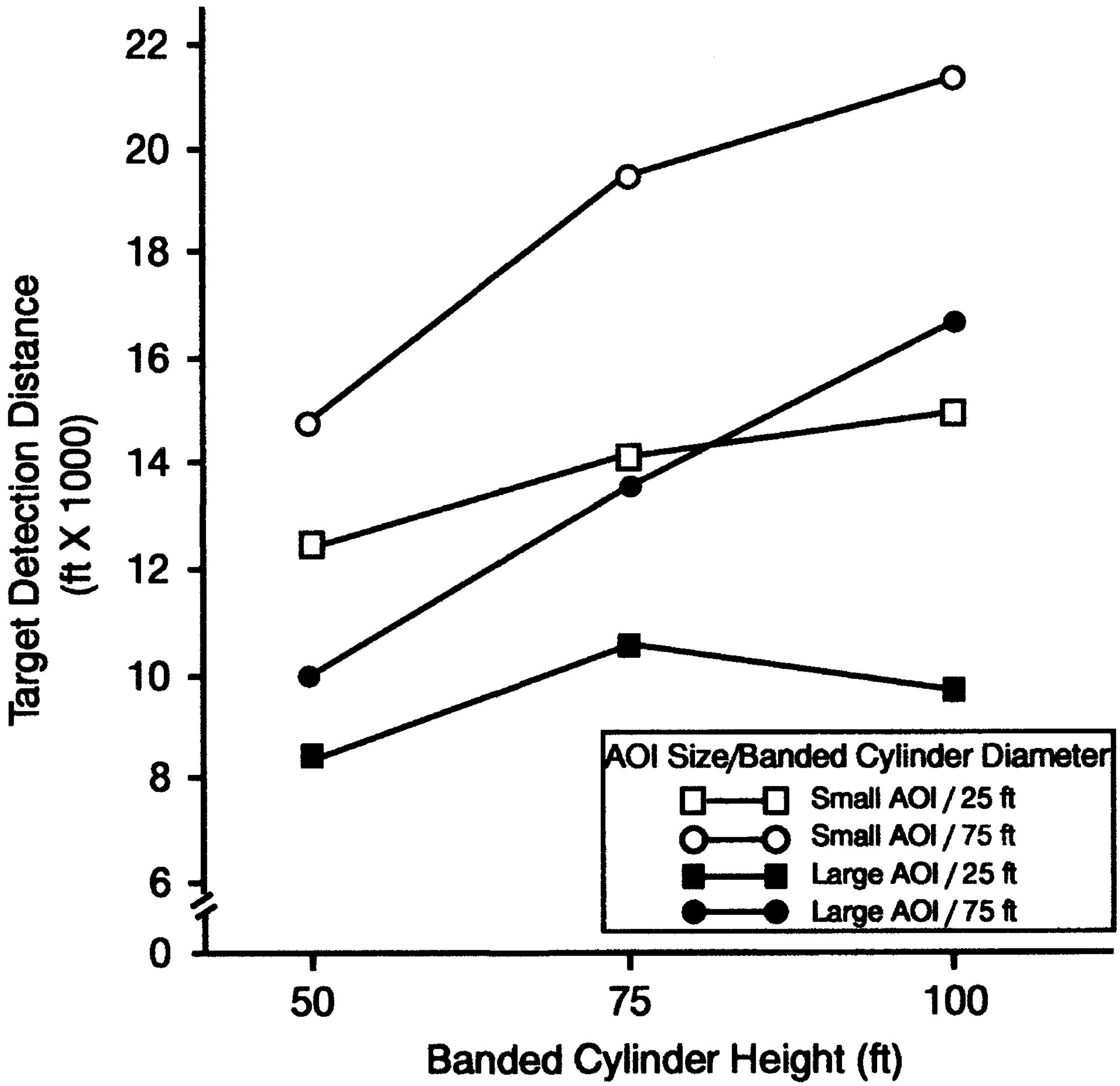

Figure 2
Mean Target Detection Distance as a Function of AOI Size, Banded Cylinder Height, and Banded Cylinder Diameter

greater than the visibility of the bands on the 100-ft-high by 25-ft-diameter cylinders in the small AOI. Second, the detection distances for the bands increased as the height of the cylinders increased, except between the two larger banded cylinder heights in the large AOI when the cylinder diameter was 25 ft. In this instance, there was a slight decline in band detection distance as the banded cylinder height increased. Third, the detection distances were greater for the bands on larger diameter cylinders than on the smaller diameter cylinders.

An alternative method for depicting the mean target detection distances in Figure 2 is shown in Figure 3. In this figure, the banded cylinder sizes are arranged in increasing order of cylinder height and diameter. A comparison between the mean target detection distances obtained in the present investigation and the corresponding threshold detection distances observed by Warner et al. (1992) is provided in Figure 4 for the small AOI and Figure 5 for the large AOI in relation to the six banded cylinder sizes. The means from the present investigation are labeled "In-Flight" in the figures, and the means designated "Threshold" are from the previous research. It is clearly evident in Figures 4 and 5 that the threshold detection distances were substantially greater than the in-flight detection distances.

Missed Targets and Response Errors

The frequencies of missed targets and response errors (i.e., when the trigger was pressed when no target was present) were too small to analyze statistically. Only three targets were missed, one with the small AOI and two with the large AOI. In each instance, the target associated with the 50-ft-high by 25-ft-diameter cylinder was missed, and each of the target misses occurred with a different observer. Out of the 432 total experimental trials, there were only 21 response errors; 9 errors in the 216 trials with the small AOI and 12 errors in the 216 trials with the large AOI. Various observers committed the response errors, and none of the subjects made more than 3 errors in the 36 trials they were each presented.

Head Movements

The head movement measures were analyzed using both multivariate analysis of variance (MANOVA) and univariate analysis of variance (ANOVA) statistical procedures. The MANOVAs were conducted to evaluate the effects of the treatment conditions on the various head movement measures simultaneously. Two MANOVAs were conducted, one for the horizontal head movements and one for the vertical movements. In contrast, the effects of the treatment conditions on each of the horizontal and vertical head movement

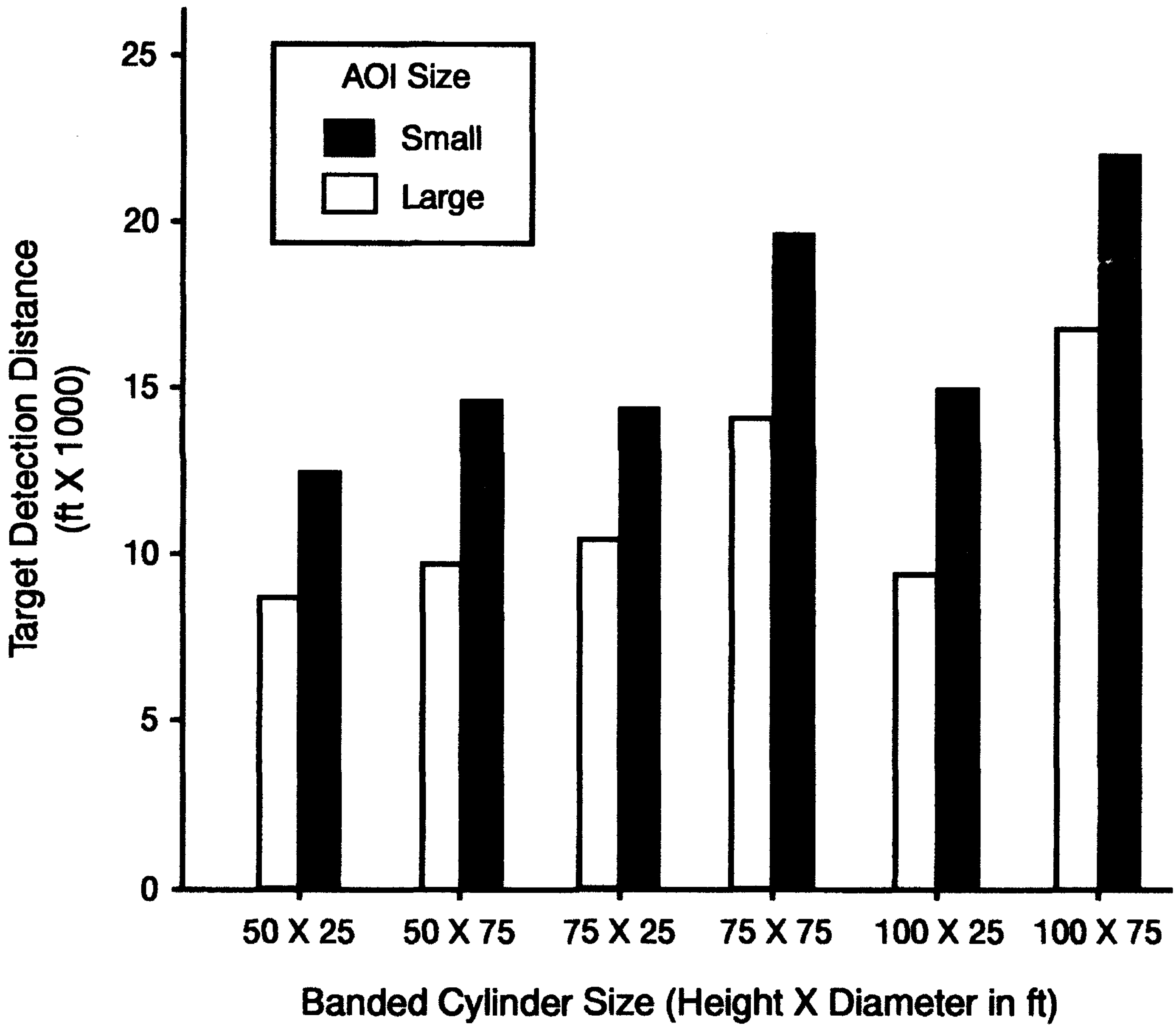

Figure 3
Comparison of the Mean Target Detection Distances
Between the Small and Large AOI Sizes for each Cylinder Size

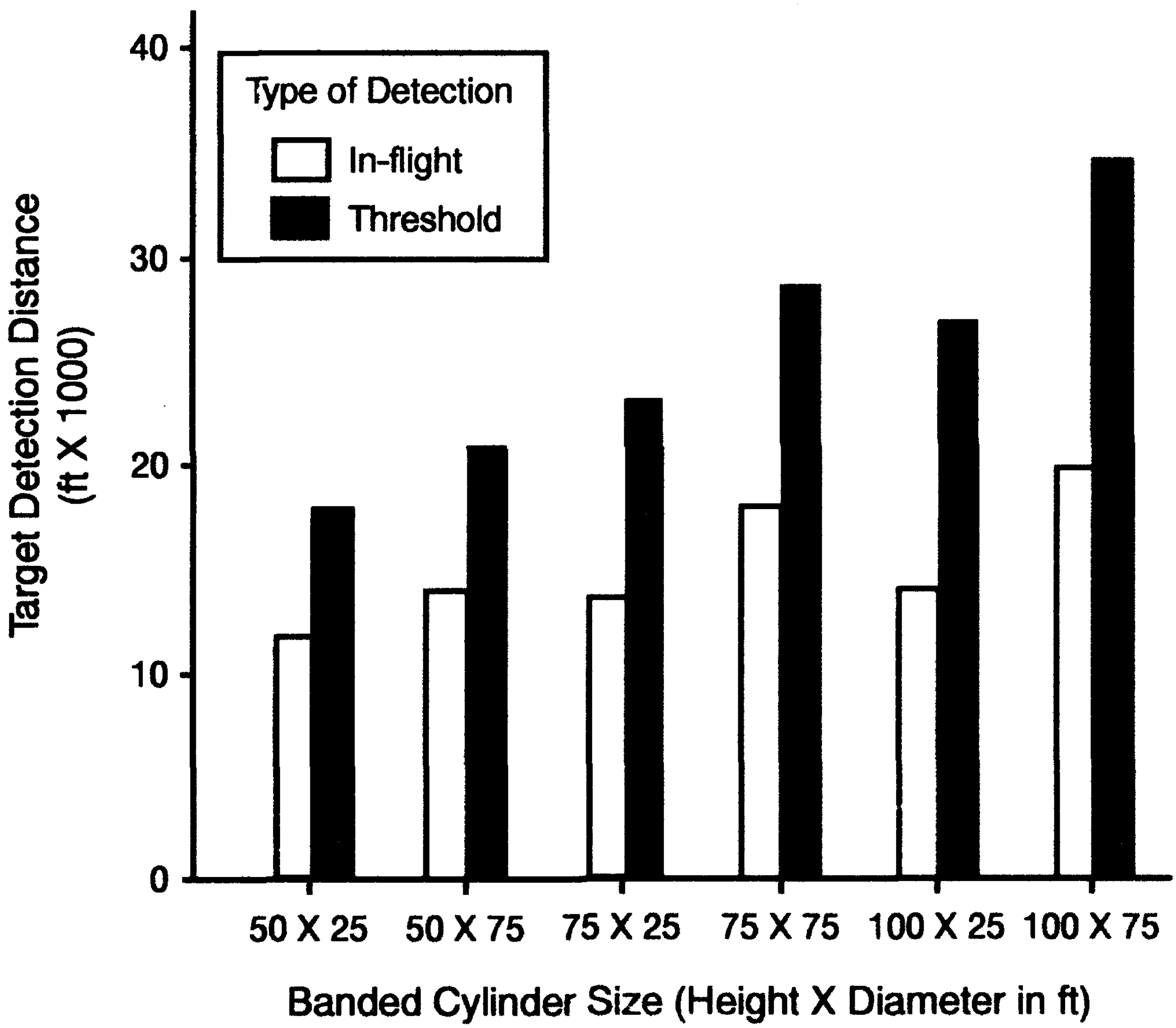

Figure 4
Comparison of the Mean In-Flight and Threshold
Detection Distances with the Small AOI

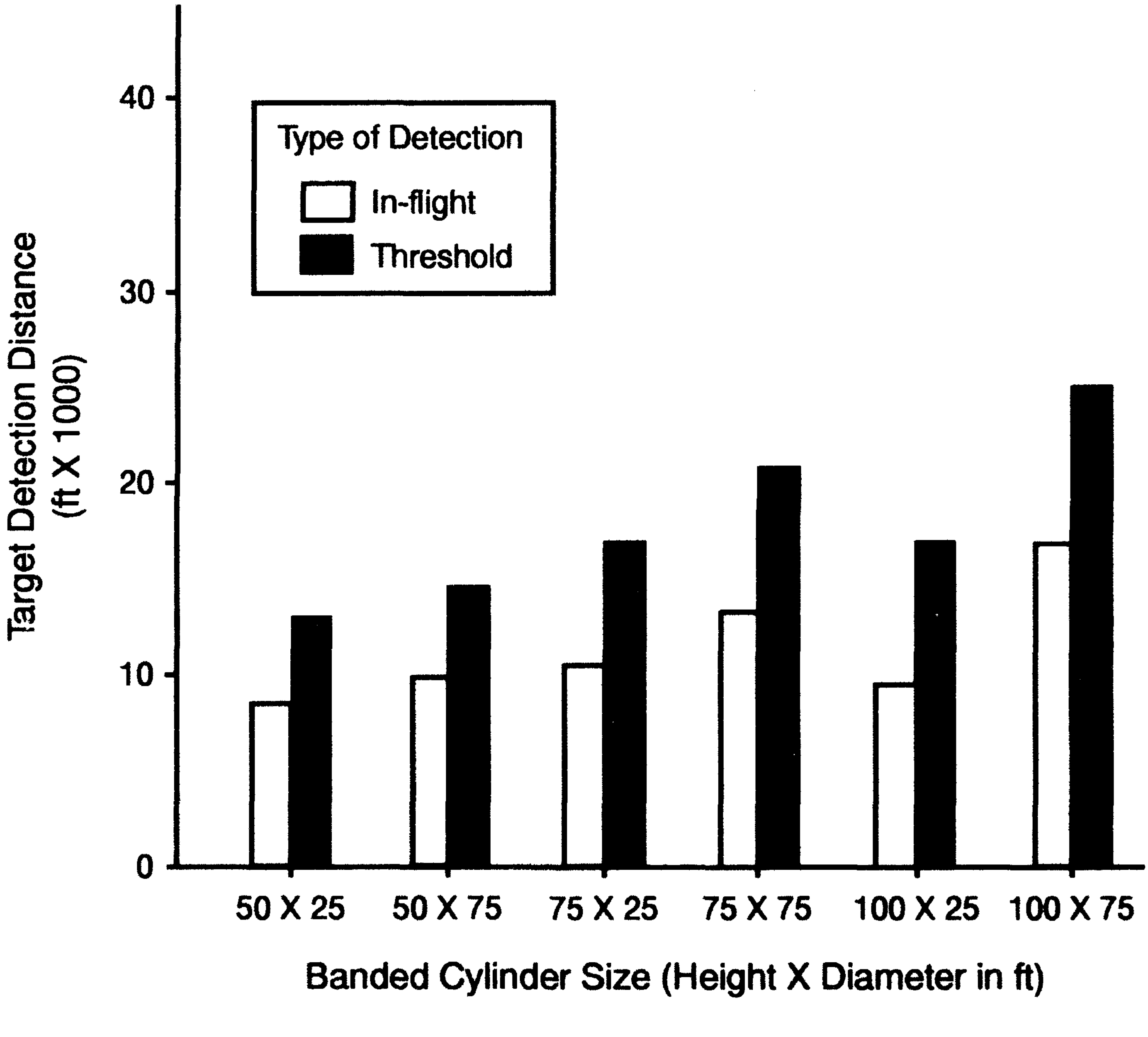

Figure 5
Comparison of the Mean In-Flight and Threshold Detection Distances with the Large AOI

measures were evaluated using the ANOVAs. In both the multivariate and univariate analyses, a two-factor model with repeated measures was implemented. The within-subjects factor was AOI size and the between-subjects factor was type of observer. In the analyses, the nine trials in both data sets were pooled. The results of these analyses are elucidated below.

Horizontal Head Movements. The MANOVA for the horizontal head movements encompassed the following five measures:

1. Horizontal head reversal frequency
2. Mean horizontal head excursion duration
3. Standard deviation horizontal head excursion duration
4. Mean horizontal head excursion amplitude
5. Standard deviation horizontal head excursion amplitude

The analysis indicated that the main effect of AOI size was significant, Wilks' $\lambda = 0.103$, approximate $F(5,6) = 10.47$, $p < 0.01$. This signifies that the five horizontal head movement measures, considered as a group, were different for the two AOI display conditions. The main effect of type of observer was not significant, nor was the interaction.

Five ANOVAs were subsequently conducted, one for each of the five horizontal head movement measures. The main effect of AOI size was significant for four of the five head movement measures: (a) horizontal head reversal frequency, $F(1,10) = 8.19$, $p < 0.05$; (b) mean horizontal head excursion duration, $F(1,10) = 7.78$, $p < 0.05$; (c) standard deviation horizontal head excursion duration, $F(1,10) = 31.99$, $p < 0.01$; and (d) mean horizontal head excursion amplitude, $F(1,10) = 9.93$, $p < 0.05$. The only main effect of AOI size that did not attain statistical significance was for standard deviation horizontal head excursion amplitude. The analyses also revealed that neither the main effect of type of observer nor the AOI size by type of observer interaction were significant for any of the horizontal head movement measures.

The means associated with the significant main effects of AOI size are presented in Table 4. The horizontal head reversal frequencies in the table reflect the average number of reversals occurring within the corridors rather than for individual targets. Dividing the average head reversal frequencies by the number of targets in the trials indicates that there was an average of 4.51 reversals per target with the small AOI and 5.10 reversals with the large AOI.

Table 4. Horizontal Head Movement Means for the Significant AOI Size Main Effects

Head movement measure	AOI size Small	AOI size Large
Horizontal head reversal frequency	18.03	20.41
Mean horizontal head excursion duration (s)	2.83	2.48
Standard deviation horizontal head excursion duration (s)	1.52	1.27
Mean horizontal head excursion amplitude (deg)	43.05	49.76

Vertical Head Movements. The following five measures were included in the MANOVA for the vertical head movements:

1. Vertical head reversal frequency
2. Mean vertical head excursion duration
3. Standard deviation vertical head excursion duration
4. Mean vertical head excursion amplitude
5. Standard deviation vertical head excursion amplitude

The results of this analysis were similar to those observed for the horizontal head movement measures. The main effect of AOI size was significant, Wilks' $\lambda = 0.170$, approximate $F(5,6) = 5.85$, $p < 0.05$. This indicates that the vertical head movements also varied with changes in AOI size. Similarly, the main effect of type of observer and the AOI size by type of observer interaction did not attain statistical significance.

Separate ANOVAs were conducted for the five vertical head movement measures. In these analyses, the main effect of AOI size was significant for four of the five measures: (a) vertical head reversal frequency, $F(1,10) = 14.95$, $p < 0.01$; (b) standard deviation vertical head excursion duration, $F(1,10) = 15.84$, $p < 0.01$; (c) mean vertical head excursion amplitude, $F(1,10) = 30.07$, $p < 0.01$; and (d) standard deviation vertical head excursion amplitude, $F(1,10) = 21.22$, $p < 0.05$. The main effect of AOI size was not significant for mean vertical head excursion duration.

Table 5 presents the means associated with the significant main effects of AOI size. In this table, the vertical head reversal frequencies represent the average number of reversals in the trials. For the individual targets, there was an average of 5.24 reversals per target with the small AOI and 6.29 reversals with the large AOI.

Table 5. Vertical Head Movement Means for the Significant AOI Size Main Effects

Head movement measure	AOI size	
	Small	Large
Vertical head reversal frequency	20.96	25.14
Standard deviation vertical head excursion duration (s)	1.44	1.24
Mean vertical head excursion amplitude (deg)	2.10	2.43
Standard deviation vertical head excursion amplitude (deg)	0.86	1.04

None of the main effects for type of observer were statistically significant. However, the AOI size by type of observer interaction was significant for three vertical head movement measures: (a) mean vertical excursion duration, $F(1,10) = 6.55$, $p < 0.05$; (b) mean vertical head excursion amplitude, $F(1,10) = 19.86$, $p < 0.01$; and (c) standard deviation vertical head excursion amplitude, $F(1,10) = 23.49$, $p < 0.01$. The head movement means corresponding to these three interactions are graphically portrayed respectively in Figures 6 through 8. These figures clearly indicate that the effect of AOI size is greater for nonpilots than for pilots.

DISCUSSION

Target Detection

The present results indicate that the detection distances associated with the target bands were influenced by the size (or resolution) of the AOI display, the height and diameter of the cylinders on which the bands were placed, and the location of the targets in the visual environment. In the analysis, AOI size significantly interacted with banded cylinder height and banded cylinder diameter. Also, there was a significant interaction between target location and banded cylinder diameter.

The three-way interaction shows (Fig. 2) that the target detection distances were greater with the small, higher resolution AOI, except that the target bands on the 100-ft-high by 75-ft-diameter cylinders were discriminable at a greater distance in the lower resolution AOI than the bands on the 100-ft-high by 25-ft-diameter cylinders in the higher resolution AOI. This exception was not present in the initial threshold investigation in the Armstrong Laboratory AOI research program (Warner et al., 1992) where the targets were presented one at a time in the center of the AOI. One explanation for this exception is that the narrow banded

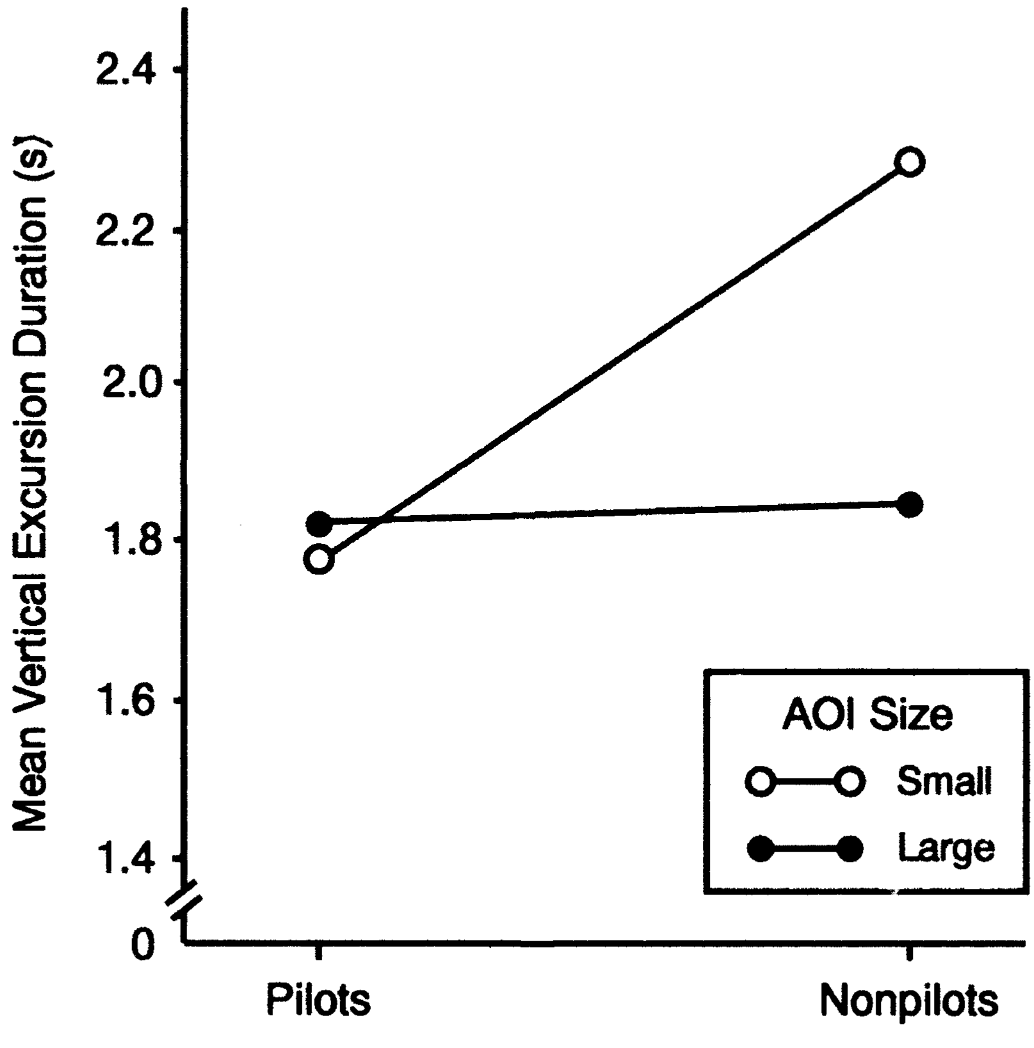

Figure 6
Mean Vertical Head Excursion Duration as a Function of AOI Size and Type of Observer

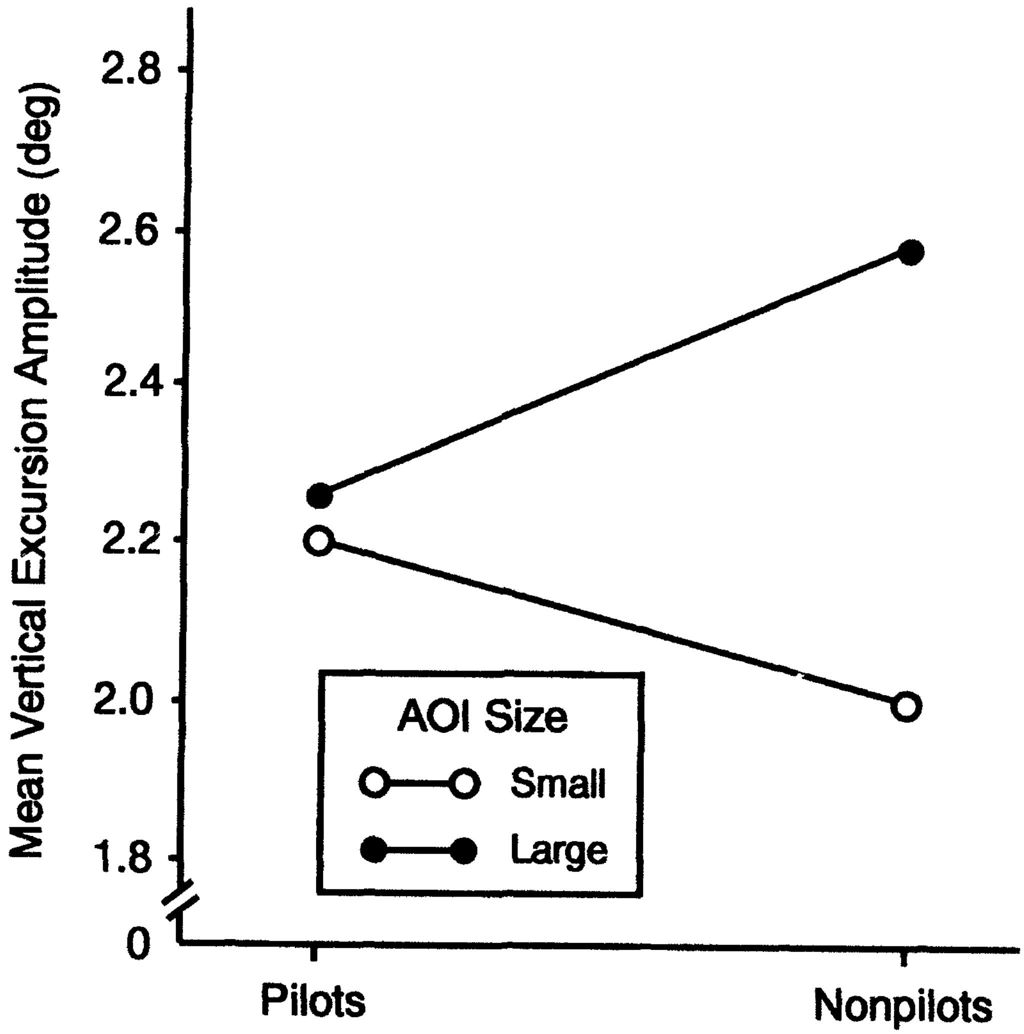

Figure 7
Mean Vertical Head Excursion Amplitude as a Function of AOI Size and Type of Observer

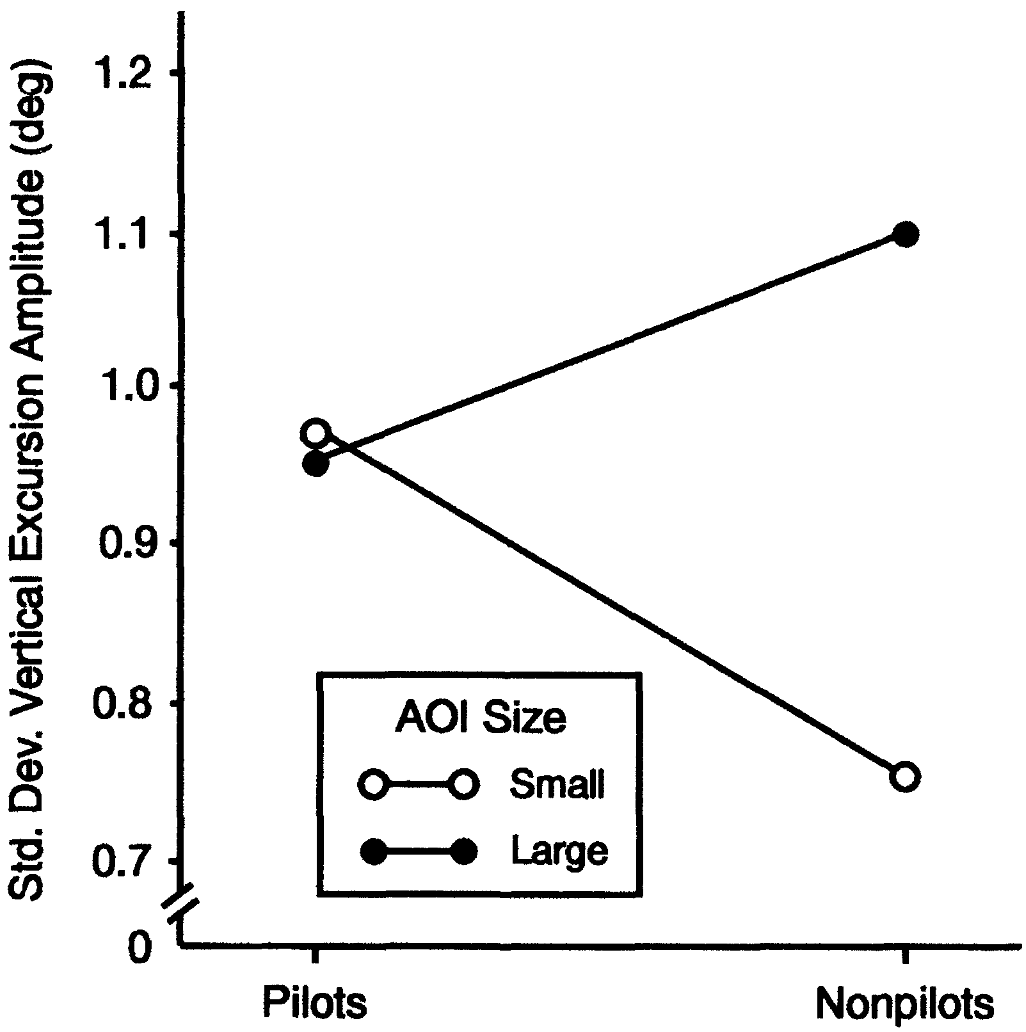

Figure 8
Standard Deviation Head Excursion Amplitude as a Function of AOI Size and Type of Observer

cylinders were partially obscured or occluded at long distances by the plain cylinders intervening between the observer and the banded cylinders.

Another factor contributing to the three-way interaction was that as the height of the cylinders increased, the detection distances for the bands on the 75-ft-diameter cylinders increased to a greater extent than the detection distances for the bands on the 25-ft-diameter cylinders. The reason for this was that the total area of the cylinders, which influenced the discriminability of the bands, increased more rapidly for the wider cylinders than the narrower cylinders when the height of the cylinders was raised. The area of the wider cylinders was 3,750, 5,625, and 7,500 sq. ft. for the three cylinder heights, and the area of the narrower cylinders was 1,250, 1,875, and 2,500 sq. ft.

A third factor contributing to the three-way interaction was the decline in the detection distances associated with the lower resolution AOI display when the height of the 25-ft-diameter banded cylinders was increased from 75 to 100 ft, which is represented by the lower right-hand line in Figure 2. A similar decline in band detection threshold distance was also observed in the initial Warner et al. AOI investigation. It is believed that the reduced visibility of the target band on the taller cylinder was due to the performance characteristics of either the light-valve projector or the computer-image generator.

In the significant two-way interaction that was obtained between target position and banded cylinder diameter (Fig. 1), the detection distances for the target bands progressively increased as the lateral distance of the targets from the centerline of the corridors increased. This occurred only for the bands on the narrower, 25-ft-diameter cylinders. The mean detection distances for the bands on the 75-ft-diameter cylinders were not significantly different between the three lateral positions. It is surmised that the farther the narrow banded cylinders were from the centerline of the corridor, the less they were obscured by the intervening plain cylinders. The reasoning behind this assertion is that the greater the lateral distance of the cylinders, the more outward and downward movement they exhibited as the observer traversed the cylinder corridors. Therefore, the relative positions of the cylinders changed more rapidly in the periphery of the display, and the banded cylinders placed at a greater distance from the center of the corridor were not masked by the intervening plain cylinders for as long a time as the more centrally located banded cylinders.

The results further revealed that the in-flight target detection distances obtained in the present investigation were substantially less than the corresponding threshold detection distances that were observed in the previous AOI evaluation. The diminished in-flight detection distances could have occurred for a number of reasons. First, the observers were required to scan a large number of cylinders to locate the cylinder bands. Second, the observer traversed the corridor at a very high simulated rate of speed, i.e., 500 kt, and thereby approached the targets very rapidly. Third, the banded cylinders may have been obscured by the intervening plain cylinders. Finally, rapid movement of the AOI display produced cylinder "smearing," which may have reduced the visibility of the target bands. Image smear was apparently due to the long phosphor persistence of the light valve coupled with the movement of the AOI. When the AOI was rapidly moved, the cylinders were elongated in the direction the AOI was moved and the dark area on the cylinder representing the target band simultaneously shrunk, making it less visible at the longer simulated distances.

A very small number of targets (only three) was actually missed by the observers. This suggests that: (a) the target bands were clearly distinguishable on all cylinder sizes and at all lateral locations from the corridor centerline, (b) the observers had ample time to search for the targets, and (c) the observers carefully searched among the cylinders for the targets. In addition, target detection performance did not differ between the two types of pilots used in the investigation, i.e., pilots versus nonpilots. From this, it can be concluded that the pilots' flight experience did not facilitate target detection.

Head Movement

AOI size exerted a significant influence on the observers' horizontal head movements as they searched for the targets. The large AOI contributed to larger mean head excursions, more frequent head reversals, and shorter mean excursion times than the small AOI. The excursion times were less variable with the large AOI as evidenced by the significantly smaller average standard deviation.

When the large, lower resolution AOI was used, the observers had to approach the cylinders more closely in the simulated aircraft to distinguish the bands. Because the cylinders migrated to the sides of the display as the observer approached the cylinders, larger horizontal head excursions were required to locate the targets with the large AOI. So as not to miss these targets as they moved outward, the observers scanned from side to side more rapidly, which resulted in a higher frequency of head reversals and shorter mean excursion times. The smaller standard deviation excursion duration associated with the large AOI indicates that excursion times were less variable when they were shorter.

No differences in horizontal head movement characteristics were elicited between the two different groups of observers used in the present investigation. This signifies that the pilots' prior flight experience did not influence the amplitude, frequency, duration, or variability of the side-to-side head excursions while searching for the targets. Also, the interaction between AOI size and type of observer was not significant for any of the horizontal head movement measures, which indicates that the horizontal head movement characteristics were the same for both groups of observers in conjunction with both AOI sizes.

The amplitudes of the vertical head excursions were substantially smaller than the horizontal head movements. This occurred because the vertical search area of the display containing the cylinders, which extended from the horizon downward, was considerably smaller than the horizontal search area, which was from one side of the simulated aircraft to the other. Due to the smaller search area in the vertical axis, only small head movements were required to visually scan for the targets. In contrast, when the observers searched toward the sides of the cylinder corridors for the targets, larger horizontal head movements were required.

The two-way interaction between AOI size and type of observer obtained in conjunction with the mean vertical excursion amplitude dependent measure indicates (Fig. 7) that the pilots' mean head excursions were nearly the same with both the small and large AOI sizes. The nonpilots' mean excursions, on the other hand, were larger than those of the pilots when the large AOI size was used, suggesting that the nonpilots tended to scan a larger longitudinal area of the corridor. Conversely, with the small AOI, the nonpilots' mean head excursion amplitudes were smaller than those of the pilots, which indicates that the nonpilots confined their search to a smaller longitudinal area of the corridor.

A significant interaction between AOI size and type of observer was also observed for the standard deviation vertical excursion amplitude measure (Fig. 8). For the pilots, the variability of the amplitudes of the vertical head excursions was approximately the same with both the small and large AOI sizes. The vertical excursions were significantly more variable for the nonpilots than for the pilots with the large AOI, and the excursions were significantly less variable for the nonpilots than the pilots when the small AOI was used. Comparison of the mean excursion amplitudes (Fig. 7) with the standard deviation amplitudes (Fig, 8) shows that as the mean amplitudes of the vertical head excursions increased, the variability of the excursion amplitudes likewise increased.

The pilots and nonpilots also differed with respect to the duration of their head excursions between vertical head reversals, but only when the small AOI was used. The significant interaction that was obtained between AOI size and type of observer revealed (Fig. 6) that the mean durations of the pilots' head excursions were nearly the same with both the small and large AOI conditions. The interaction also showed that the mean duration of the nonpilots' head excursions with the large AOI was practically the same as the mean duration of the pilots' head movements with the large AOI. The duration of the nonpilots' head excursions was significantly longer, however, with the small AOI than with the large AOI. When the excursion times and amplitudes are compared (Figs. 6 and 7), it is apparent that the nonpilots' mean excursion times were inversely related to the mean excursion amplitudes. That is, the larger the excursion amplitudes, the smaller the mean duration of the excursions.

As in the case of the horizontal head movements, there were significantly more vertical head reversals with the large AOI than with the small AOI. In addition, the frequency of head reversals did not differ significantly between the two types of observers and the interaction between AOI size and type of observer did not achieve statistical significance. It is surmised that the observers changed the direction of their search upward and downward more times with the large AOI in order to detect the targets as far as possible in the corridor and, at the same time, not allow the targets to pass by the aircraft undetected since the observers had to approach the targets much more closely with the large AOI.

In retrospect, it was anticipated prior to the start of data collection that the head movement requirements would be greater with the small AOI. Because a smaller area of the visual scene is encompassed within the small AOI at any one time compared to the larger AOI, it was assumed that more head movement would be required with the small AOI than the large AOI to scan the same display area. Contrary to our expectations, it was observed that the small AOI elicited less head movement than the large AOI. The rationale for this finding is that with the small AOI, the observers scanned farther ahead in the cylinder corridors where the width of the corridor was smaller due to the convergence of the margins of the corridor toward the horizon, which characterizes linear perspective.

RECOMMENDATIONS

Due to equipment constraints, only two AOI sizes were available for use in this evaluation. Of the two, the small, higher resolution is recommended for training tasks in which detection distance and image detail are crucial. The head movement requirements for the type of task used in the present research are also less demanding with the small AOI. One drawback associated with the small AOI, however, is that the observer can see around the AOI into the low-resolution background more easily than with the large AOI. Therefore, in applications where detection distance is not important, the large AOI may be more acceptable to the observer.

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